Recd: - 23 NOV 1953

M.R.P. 820
S.C.III/156
10th June, 1953.

At the time of issue this report has not been published. Any author desiring to quote this paper should refer to it as "A paper of the Meteorological Research Committee (London), M.R.P. No..... by Mr.....
A copy is available in the Library of the Meteorological Office."

AIR MINISTRY

METEOROLOGICAL RESEARCH COMMITTEE

Five Flights through a Thunderstorm Belt

by
R.F. Jones (Meteorological Office)

1. Introduction

In a previous report (1) on cumulonimbus investigation the writer gave the results of some integrations of the accelerometer records obtained in a Spitfire aircraft on flights through cumulus and cumulonimbus clouds. The curves obtained, curves of vertical speed, required adjustment to take account of any errors in reading the accelerometer trace and it was necessary to make several plausible assumptions, as to the changes of height of the aircraft, to obtain reasonable curves of the vertical speeds to which the aircraft was subjected. Lack of information of height changes experienced precluded any check on the validity of these assumptions.

With the change of aircraft type for these investigations from Spitfire to Meteor VII it became possible to carry an observer and to install an auto-recorder to give photographically at 10 second intervals the readings of I.C.A.N. height, air temperature and indicated air speed. Any accelerometer record from the Meteor, therefore, can be integrated and the curve obtained adjusted to ensure that the vertical speeds obtained give, by a further integration, correct height changes over successive periods of 10 seconds or more.

By performing a few integrations of accelerometer records obtained in the Meteor it is therefore possible to check whether the assumptions made in the previous report were reasonable as well as obtain information on vertical currents which will be of interest on their own account.

Five flights made on 13th June, 1952 through a belt of thunderstorms were chosen for analysis in this way and are the subject of this report.

2. Synoptic situation and flight programme

The whole of England and Wales was covered by a shallow depression forming part of a low pressure belt extending from Scandinavia to the Azores. The upper winds were variable and generally light up to 12,000 ft. while the 500 mb. and 300 mb. contour charts showed the existence of a cold pool over SW. England and the western English Channel. Conditions were therefore favourable for outbreaks of thundery rain or thunderstorms and

/these

these were confirmed by the extensive radar weather echoes visible at East Hill. Later in the day the echoes became less extensive and it was decided to investigate a belt of radar echo lying NW. to SE. to the northeast of East Hill (see P.P.I. photograph taken at 1607 GMT). The radar echo tops (see height-range photographs) reached to 35,000 to 36,000 ft., which was probably the tropopause height (1500 GMT tropopause heights: Larkhill 32,300 ft., Hemsby 39,000 ft.).

The aircraft was in the vicinity of the clouds giving this belt of echo at 1525 GMT and described them as a line of five cumulonimbus clouds lying NW. to SE. There was extensive anvil cirrus.

The first two runs were made at 25,200 ft. through the last but one towards the SE. of the cumulonimbus clouds on headings of 270° and 090° but, because the aircraft came too close to the minimum radar visible range, the three subsequent runs were made through the last cumulonimbus of all on headings of 260°, 080°, 260° at 20,200, 20,200 and 18,200 ft. respectively. All the runs took place between 1528 and 1604 GMT and the tracks followed by the aircraft through the echoing volume, after adjustment for echo movement, are shown in the P.P.I. photograph. From the appearance of the radar echo it is certain that the clouds to SE. of the belt were the most recently developed (on the P.P.I. photograph reproduced, taken just after the runs were completed, yet another new cell is seen to be developing at the southeastern extremity of the belt).

3. Information available

For each of the five flights analysed the following information is available.

(i) A continuous record, on 35 mm film, of accelerations in the vertical experienced by the aircraft. The speed of the film was 2.53 ft./min. (0.506 in./sec.) and the scale such that a vertical movement of the trace through 2.7 mm corresponded to an acceleration of 1g (32 ft./sec.^{2}).

The film was examined under an enlarger and the accelerations recorded to the nearest .05g as often as necessary to give a faithful reproduction down to 0.1 sec. This detail with respect to time cannot be shown accurately in Figs. I to V but the accurate time values have been used in the integrations.

(ii) The altimeter reading at 10 sec. intervals.

(iii) The indicated air speed at 10 sec. intervals. This affords an indication of the climb and dive attitude of the aircraft since the power setting of the aircraft was not usually adjusted during a run. Although constant attitude in traversing the clouds was aimed at there were nevertheless some variations in indicated air speed. Once a power setting has been chosen an indicated air speed greater than that necessary to maintain level flight indicates a diving attitude if the power setting remains unchanged. It is possible therefore to see, at least qualitatively, whether the up or down movements of the aircraft were ascribable to air currents or to changes in climb and dive attitude of the aircraft. It is hoped later to make test runs with the same aircraft to determine the variation of height with indicated air speed at a constant power setting.

(iv) The air temperature at 10 sec. intervals. The thermometer used was a ratiometer-type temperature indicator - Sangamo-Weston Type S 110 Form 9. The temperature element is a platinum wire wound on a conical head and enclosed in hydrogen. The speed corrections have been carefully determined and it is considered that

/the

the readings outside cloud are correct to $\pm\frac{1}{4}$°C with a lag of about $1\frac{1}{2}$ sec. Measurements in cloud are, of course, subject to all the usual troubles and uncertainties (see, for example, Ref. (2)). The corrected temperature readings have also been further corrected to minimise the effect of altitude changes. This consists of adjusting the temperature readings to those that would have been experienced at the mean level of flight, by applying a dry adiabatic correction (3°C/1000 ft.) for readings outside cloud and the wet adiabatic, appropriate to the height and mean temperature of the flight, when inside cloud. As the departures from the mean level of flight were always less than 300 ft. the corrections applied on this account were never as great as 1°C.

The application of the normal speed corrections to temperatures taken within cloud means that the corrected temperatures may often be too cold by variable amounts which might be as great as 3.1°C at 18,000 ft., 2.3°C at 20,000 ft. and 0.8°C at 25,000 ft.

(v) A tape recording of the comments made by the observer in the aircraft during a cloud traverse and received from the aircraft on R/T. This includes notes of times of switching on and off accelerometer and times of entry into and exit from cloud.

(vi) Radar cross-sections in the vertical of the storm echo along the line of flight of the aircraft, taken on wavelengths of 10 cm. and 3 cm. (beam widths to half power 1.5° and 0.7° respectively in the vertical plane and 7.5° and 2° respectively in the horizontal plane). An average of eight photographs is available for each run. On many of these the aircraft echo is also visible, thus enabling the position of the aircraft relative to the radar weather echo to be known accurately at any instant.

4. Presentation of the data

The data for each of the five flights are shown separately in Figs. I to V respectively.

In each figure the first graph shows the accelerations experienced by the aircraft against time. The second graph is the integration of the acceleration curve giving a curve of vertical speed against time. The third graph shows the altimeter readings at 10 sec. (sometimes 9 sec.) intervals. The altimeter changes in a given time should be related to the integral of the second graph over the same period of time and the dotted lines over different time periods, usually 20 sec., on the second graph are the zero corrections which must be applied to give the correct altimeter changes. The fourth graph shows the curve of the second graph adjusted to make the altimeter changes correct. The transition from one zero correction to the next has been smoothed, taking account of the form of the original integrated curve. It is considered that this curve gives a true representation of the upward and downward speeds of movement of the aircraft. The fifth and sixth graphs of each figure give the indicated air speed and corrected air temperatures at 10 sec. (sometimes 9 sec.) intervals respectively.

Also indicated are the parts of the records obtained within cloud and the instants of entry into and departure from the echoing volume associated with the cloud. On Figs. II and V graph (4) are indicated the places where lightning was reported by the observer in the aircraft.

/5.

5. Evaluation of up and down air currents

The interest in the integrated curves lies in the deductions which can be made from the behaviour of the aircraft about the air currents encountered by the aircraft. If an aircraft flying level enters an upward air current and maintains its attitude it will ultimately take up the upward speed of the air, if the air current has a large enough horizontal extent. The time taken for the aircraft to take up this upward speed will depend on the characteristics of the aircraft but for the aircraft used is of the order of one second. Provided the aircraft was flying level therefore (i.e. in these cases, if the power setting was constant, provided the indicated air speed was constant) it can be inferred that the upward air speeds were at least as great as the upward speeds of the aircraft, but not much greater if the up-current took more than a second or two to cross.

Unfortunately on many occasions, presumably because of the turbulence encountered, the indicated air speed did not remain constant. On these occasions, however, the form of the integrated curve and the knowledge that increased air speed usually means diving attitude (although a change of power setting would also change the indicated air speed) enable useful deductions still to be made from the curve of aircraft vertical speed against time.

6. Discussion of results

(a) Turbulence

The most striking feature of Figs. I to V is the marked change in frequency and intensity of gusts on entering cloud. In the clear air before entering and after leaving cloud there was only one gust as great as 0.4g in the five runs (at 257 sec. on Run II - see Fig. II) and this was very probably occasioned by an abrupt change in aircraft attitude (see indicated air speed trace). The frequency of detected gusts in the clear air was on the average one per 5.3 sec. (about 2,900 ft.) compared with an average frequency of gusts in cloud of one per 1.4 sec. (about 770 ft.).

All the gusts as great as 0.5g occurred within the part of the cloud from which an echo was received; the frequency of gusts in cloud but not in the echoing volume was one per 1.9 sec., i.e., gusts were slightly less frequent outside the echoing volume, but great significance cannot be attached to the result since only 66 sec. of all the flights qualified in the determination of this frequency.

(b) Up and down air currents

The authors of "The Thunderstorm" (3) draw a clear distinction (pp. 39, 43) between gusts and "drafts". They regard the gusts as caused by eddies superimposed on the general airflow and carried along by it. On this interpretation the vertical movements of the aircraft are regarded as caused by the large scale air currents and the strength of the air current is deduced from the change of altimeter reading, while the gusts recorded are regarded as effects entirely separate with no permanent effect on the upward and downward movement of the aircraft. While it is very likely that such gusts or eddies do exist the fact remains that recorded gusts are recorded accelerations of the aircraft in the vertical and that if due account is taken of their magnitude, shape and duration, their effect on the vertical movement of the aircraft can be determined. In fact the integrated effect of all the gusts should give the speed of movement of the aircraft in the vertical. The only exception to this can be if the aircraft can enter an up or down current without recording a detectable acceleration. Mean up currents of 30 - 40 ft./sec., as determined from the aircraft altimeter trace, were quite commonly encountered in Florida and Ohio (3) and to enter these without recording a detectable acceleration, i.e. without recording a "gust", would require a very gradual increase in speed of up current with horizontal distance. For, if the minimum detectable acceleration is .05g (1.6 ft./sec.$^{-2}$), it will take more than 40 sec. for an aircraft to acquire an upward speed of 64 ft./sec., and a

/further

further 40 sec. or more for the aircraft to lose this speed, to give a mean upward speed of 32 ft./sec. without recording "gusts". With the aircraft travelling about 300 ft./sec. this would require all up or down currents of mean value 32 ft./sec. to be at least 24,000 ft. across - a very unlikely contingency (3). On the other hand two up gusts of 1.0g, each lasting for only one second and giving a mean acceleration of 0.5g for that second, would impart to the aircraft an upward speed of 32 ft./sec. Many of the recorded gusts therefore are probably not caused by small eddies superimposed on a major up or down current but are really a demonstration of the strong gradient along the line of flight of the vertical speed of the major current itself.

It seems most likely therefore that the integrated accelerometer trace (i.e. the integrated gusts) will give all the major up or down speeds of the aircraft, however caused, as well as small scale eddy fluctuations. A convincing demonstration of this given by curves (2) and (3) of Fig. II in which the three major up and down currents (after 120 sec.) shown by the integrated accelerometer record - even before corrections are applied - have their counterpart in the variation of aircraft height as shown by the altimeter record.

The outstanding feature of the curves of vertical speed is the close proximity of up and down currents of comparable magnitude. An extreme example occurs at 200 sec. on Fig. I when the aircraft changed from a maximum upward speed of 30 ft./sec. to a maximum downward speed of 23 ft./sec. in four seconds, a distance of about 750 yd., but even in the wider up currents of Fig. II, for example, there appears to be direct transition from up current to down current. A similar feature is to be observed in the integrated traces reported in M.R.P. 593 (1). Some of these transitions may be brought about by large eddies rather than by up or down currents persisting through a great depth of cloud and, while it is unlikely that all are so caused, there is no means of separating large eddies from extensive up or down currents. However they are caused, one is forced to the conclusion that within a mature cumulonimbus cloud up and down air currents as strong as 20 ft./sec. or more may exist in close proximity to each other. The danger to a pilot attempting to fly constant altitude is obvious; for to maintain altitude in an up current of 30 ft./sec., say, he must take up a diving attitude sufficient to give a rate of descent in still air of 30 ft./sec. A quick transition to a down current of 30 ft./sec. will find him descending at 60 ft./sec. and requiring a rate of climb of 60 ft./sec. to maintain altitude. Thus the effects of up and down currents and the strain on the aircraft are accentuated.

Examination of Figs. I to V shows that most of the up currents on these occasions were about 3000 to 5000 ft. across (although two were about 10,000 ft. on Run 2) and the down currents usually 1500 - 4000 ft. across. This is broadly in agreement with the experience reported in "The Thunderstorm" (3) from a much greater number of occasions. It is not therefore surprising, with the up and down currents so narrow, that flights only a few minutes later at the same height on the reciprocal track are not similar in detail of up and down currents or turbulence encountered (e.g. Figs. I and II, Figs. III and IV).

Outside cloud up and down currents would appear to have been of more variable, and usually greater, width. After allowing for variations in indicated air speed it would appear that down currents in excess of 10 ft./sec. may exist on some occasions outside cloud but up currents as great as 10 ft./sec. were only encountered within the cloud.

(c) Temperature

Detailed temperature traces exhibit a somewhat disturbing feature because of the close correlation between the curves for indicated air speed and temperature, increasing air speed being associated with colder temperatures. Since increased air speed means a greater correction to be subtracted from indicated temperature this correlation suggests that

/it

it may be a mistake to correct in detail for air speed variations, i.e., it suggests that some of the air speed readings are sudden changes, brought about perhaps by gusts, and not applicable to a time $1\frac{1}{2}$ sec. previously - the lag of the thermometer is about $1\frac{1}{2}$ sec. A variation of 10 m.p.h. in indicated air speed gives a variation of about 0.7°C in temperature correction to be applied. It is, of course, possible that the correlation between the traces is due to an external cause affecting each e.g. a cold down current would have the same effect if it caused the aircraft to take up a diving attitude.

Detailed correlation of temperature with up and down currents, even outside cloud, therefore is open to objection. Inside cloud there is the additional difficulty of knowing what speed correction to make, or even, because of the variations of water content, whether the same correction should apply in all parts of the cloud.

The mean temperatures and standard deviations for each height are shown in Table I.

Table I.

Height (ft. ICAN)	Mean Temp. in cloud (°C)	Standard Deviation (°C)	No. of obs.	Mean Temp. clear air (°C)	Standard Deviation (°C)	No. of obs.
25,200	-30.7	0.6	27	-30.7	0.6	31
20,200	-19.5	0.9	12	-19.2	0.7	23
18,200	-16.2	0.7	7	-15.2	0.3	12

As mentioned in para. 3 (iv) above the in-cloud temperatures may be too cold by up to 3.1°C, 2.3°C and 0.8°C at 18,200, 20,200 and 25,200 ft. respectively. Taking this into account it would seem likely that the mean in-cloud temperatures were warmer than the clear air at the same height with the differences in temperature not likely to exceed 2.0°C at 18,200 and 20,200 ft. and 0.8°C at 25,200 ft. Applying the full possible corrections the lapse rates in cloud would be 2.1°C/1000 ft. between 18,200 and 20,200 ft. and 2.5°C/1000 ft. between 20,200 and 25,200 ft., which are very close to the saturated adiabatic lapse rates (saturation with respect to water) for a wet bulb potential temperature of about 62°F (2.2°C, 2.4°C and 2.8°C per 1000 ft. at 18,200, 20,200 and 25,200 ft. respectively). The lapse rates in clear air, 2.0°C/1000 ft. and 2.3°C/1000 ft. between 18,200 and 20,200 ft. and 20,200 and 25,200 ft. respectively are less than the saturated adiabatic lapse rate.

It is of interest to note that the variability of temperature within cloud, as evidenced by the standard deviation of the observations, is not significantly greater than outside cloud at 20,200 and 25,200 ft.

(d) Lightning

Lightning was reported by the observer in the aircraft over the radio telephone at the time of its occurrence on one occasion on run (2) at 25,000 ft. and four occasions on run (5) at 18,200 ft. A time lag of two seconds has been allowed for the time to report and the points of occurrence are indicated in the appropriate places on curve (4) of Figs. II and V.

It will be seen that on all occasions but one (at 128 sec. on run (5)) the aircraft was not experiencing any appreciable up or down movement while on the other occasion, although it was descending at about 20 ft./sec., it seems likely, from the air speed trace, that a large part of the downward movement was occasioned by a change in attitude of the aircraft.

/The

The fact that lightning was not reported on runs (3) and (4) which were only 2,000 ft. higher than run (5) and 11 min. and 6 min. earlier respectively suggests that run (5) was made at almost exactly the time when lightning first occurred within the cloud. From the radar echo photographs it is clear that the cloud had already reached its maximum vertical extent by the time run (3) was made.

(e) Correlation with radar echo

Previous analyses of cumulonimbus flights have, of necessity, relied on the 10 cm. wavelength radar to determine correlations between radar echo and turbulence. The limitations of this radar, particularly in respect of the horizontal beam width of the height-range equipment, have been discussed (1). During the flights here described a 3 cm. wavelength height-range radar was also used which gave greater precision because of its narrower beam width (0.7° in the vertical and 2° in the horizontal plane). Photographs of the display of this equipment taken on each run close to the time of entry into and departure from cloud (other photographs are also available) are shown while the P.P.I. photograph gives the 10 cm. wavelength picture. It will be seen that even the small change of bearing necessary to keep the aircraft in the radar beam can substantially change the radar picture. This makes correlation with radar echo more difficult but on each photograph are indicated the areas where up or down currents of greater speed than 20 ft./sec. were encountered and where gusts of 0.5g or greater occurred. The appropriate time scale for the run is also given.

It will be seen that all gusts of 0.5g or greater were encountered within portions of the cloud giving rise to the radar echo and were often, as reported in earlier papers (1), (4), associated with discontinuities in the echo structure. There is some evidence that up currents and echo columns may coincide while on run (5) a substantial down current would seem to have existed outside the edge of the echoing volume but still within cloud; (a strong down current indicated just outside echo and cloud in run (2) would seem to have been principally caused by a change of aircraft attitude).

On runs (1) and (3) the echoing volume began about 12 sec. (about $1\frac{1}{4}$ mi.) before the observer reported entering cloud, suggesting the existence of precipitation from overhanging cloud. On runs (4) and (5) the edge of the echoing volume and cloud edge coincided while on run (2) the aircraft was in cloud about 12 sec. (about $1\frac{1}{4}$ mi.) before entering the echoing volume. On the other hand the aircraft always left the echoing volume before leaving cloud by times varying between 7 and 17 sec. ($\frac{3}{4}$ - $1\frac{3}{4}$ mi.).

7. Conclusions and Summary

(i) It is possible to obtain reliably from an accelerometer trace and altimeter record the detailed movements of an aircraft in the vertical and thence, if indicated air speed is also recorded, deduce the strengths of up and down air currents.

(ii) The adjustments made to the integrated curves in M.R.P. 593 (1) were reasonable and the deductions made from them valid.

(iii) Up and down air currents of comparable magnitude, which may exceed 20 ft./sec. on occasions, occur close to each other in mature cumulonimbus clouds.

(iv) Down currents in excess of 10 ft./sec. may occur outside cloud but the up currents in excess of 10 ft./sec. recorded were all within cloud.

(v) There was a striking change in frequency and intensity of gusts on entry into cloud and the biggest gusts all occurred within the echoing volume of the clouds.

/(vi)

(vi) Mean in-cloud temperatures, although difficult to measure with certainty, were probably up to 2°C warmer than the mean environment temperature at the same height at 18,200 and 20,200 ft. and up to 0.8°C warmer at 25,200 ft.

(vii) Lightning occurred once at 25,200 ft. and four times at 18,200 ft. and on these occasions the aircraft was probably not in any appreciable up or down current. The cloud had already attained its maximum vertical development before lightning was reported.

(viii) Detailed correlation with radar echo is made difficult by the substantial changes in echo structure accompanying a small change in the azimuth of viewing when using a narrow beam width 3 cm. wavelength equipment.

8. References

(1) Jones, R.F.: The relation between the radar echoes from cumulus and cumulonimbus clouds and the turbulence within those clouds. Part II. M.R.P. No.593, Air Ministry, Meteorological Research Committee, London, 1950.

(2) Meteorological Office: Meteorological Air Observer's Handbook. M.O. 470, Air Ministry, London, 1945. pp. 17 - 18.

(3) Thunderstorm Project: "The Thunderstorm ". U.S. Department of Commerce, Weather Bureau, Washington, D.C., 1949.

(4) Jones, R.F.: The relation between the radar echoes from cumulus and cumulonimbus clouds and the turbulence within those clouds. M.R.P. No. 484, Air Ministry, Meteorological Research Committee, London, 1949.

M.R.P. 820.

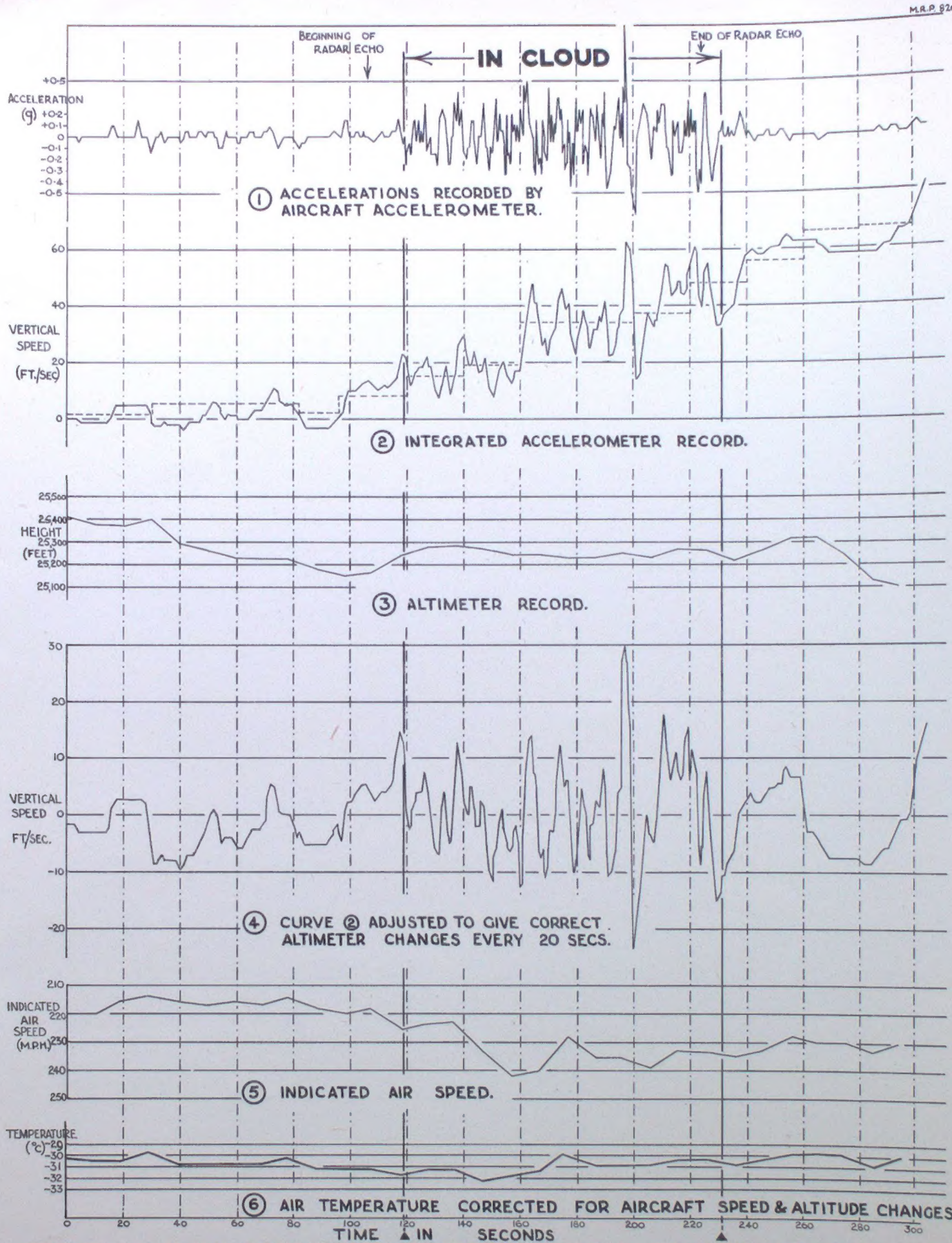


FIG.I. CUMULONIMBUS INVESTIGATION – 13TH JUNE 1952 – RUN 1. 25,200'.

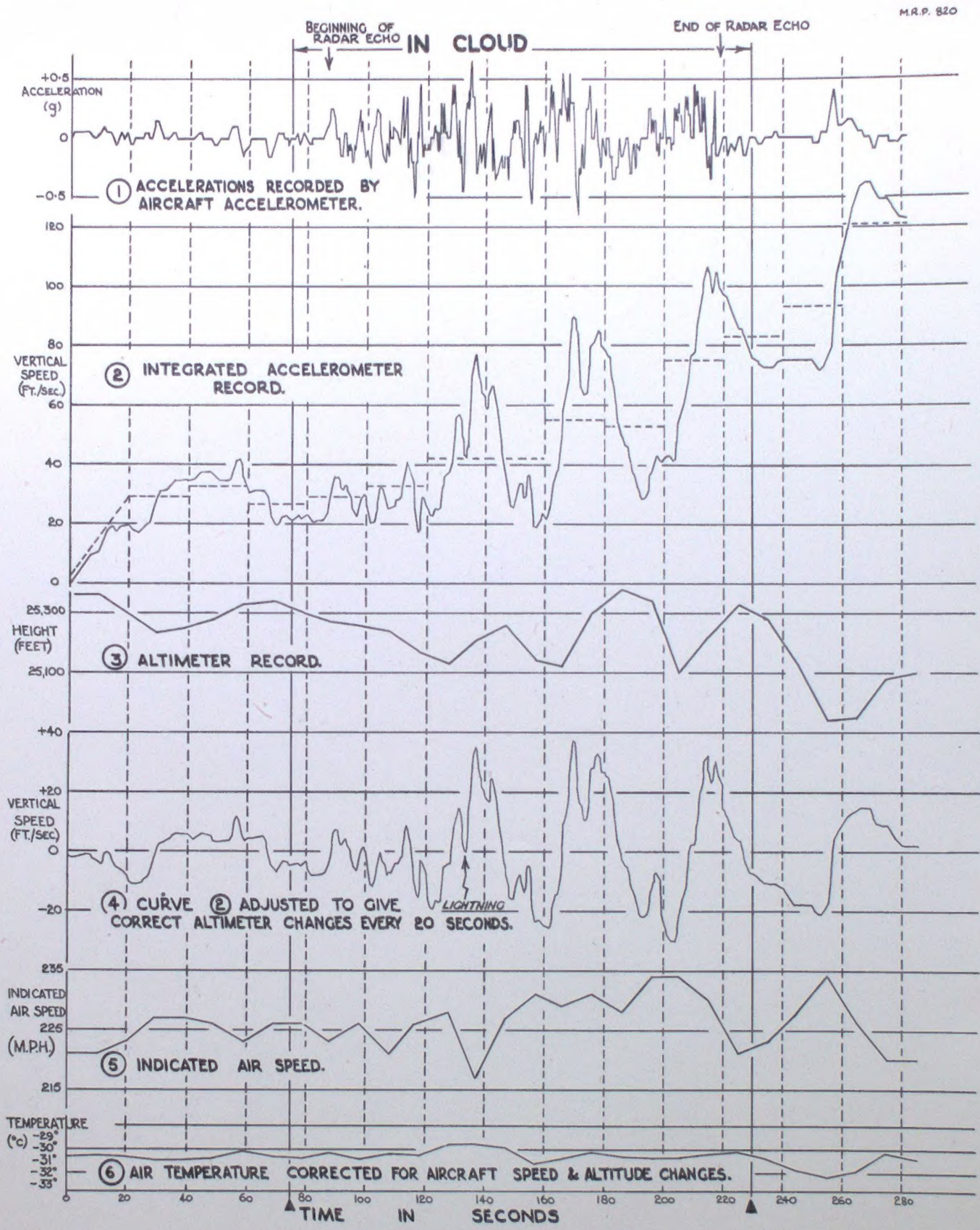


FIG. II. CUMULONIMBUS INVESTIGATION - 13TH JUNE 1952 - RUN II. 25,200'

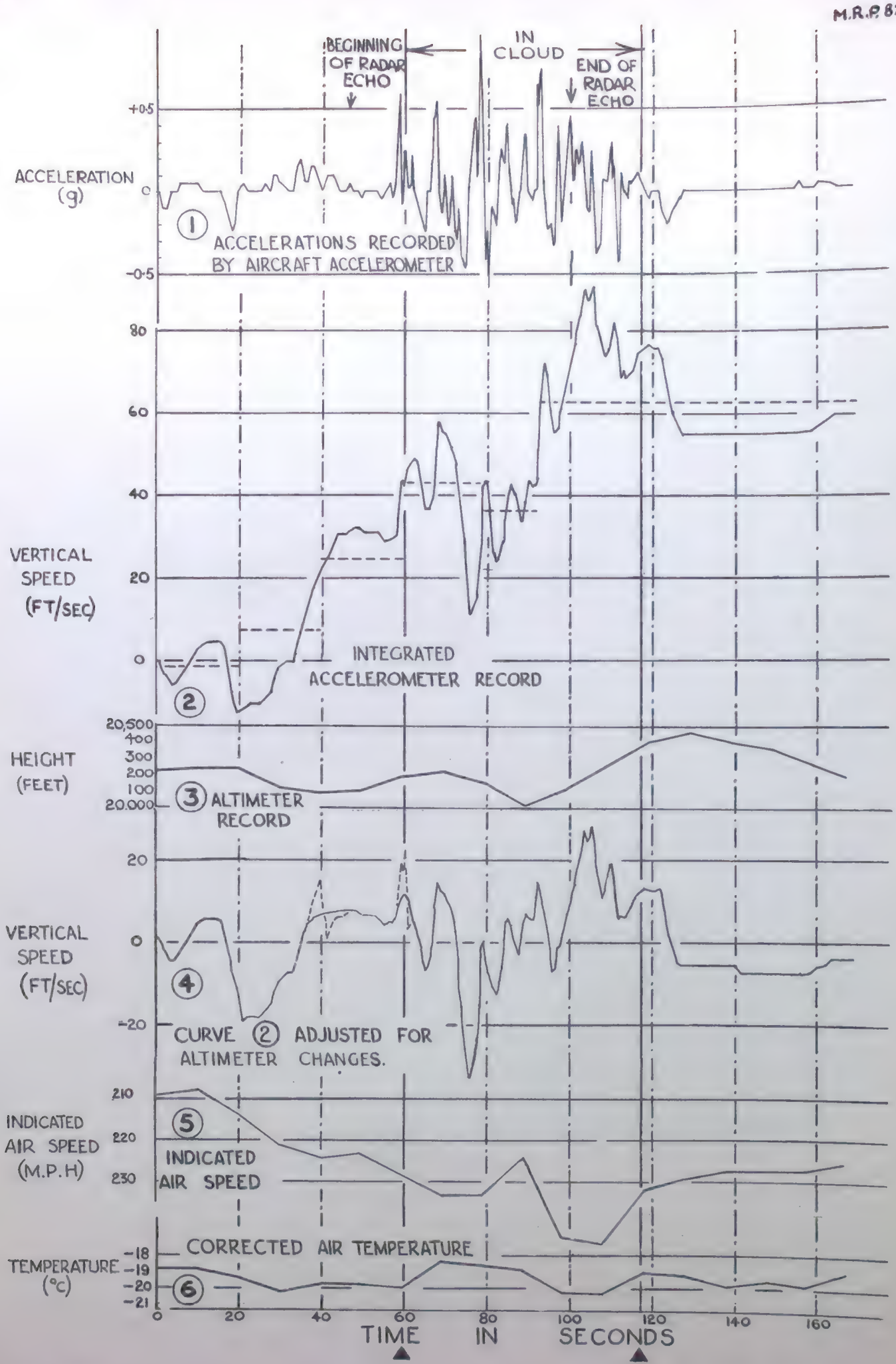


FIG. III. CUMULONIMBUS INVESTIGATION - 13TH JUNE 1952 - 20,200'.

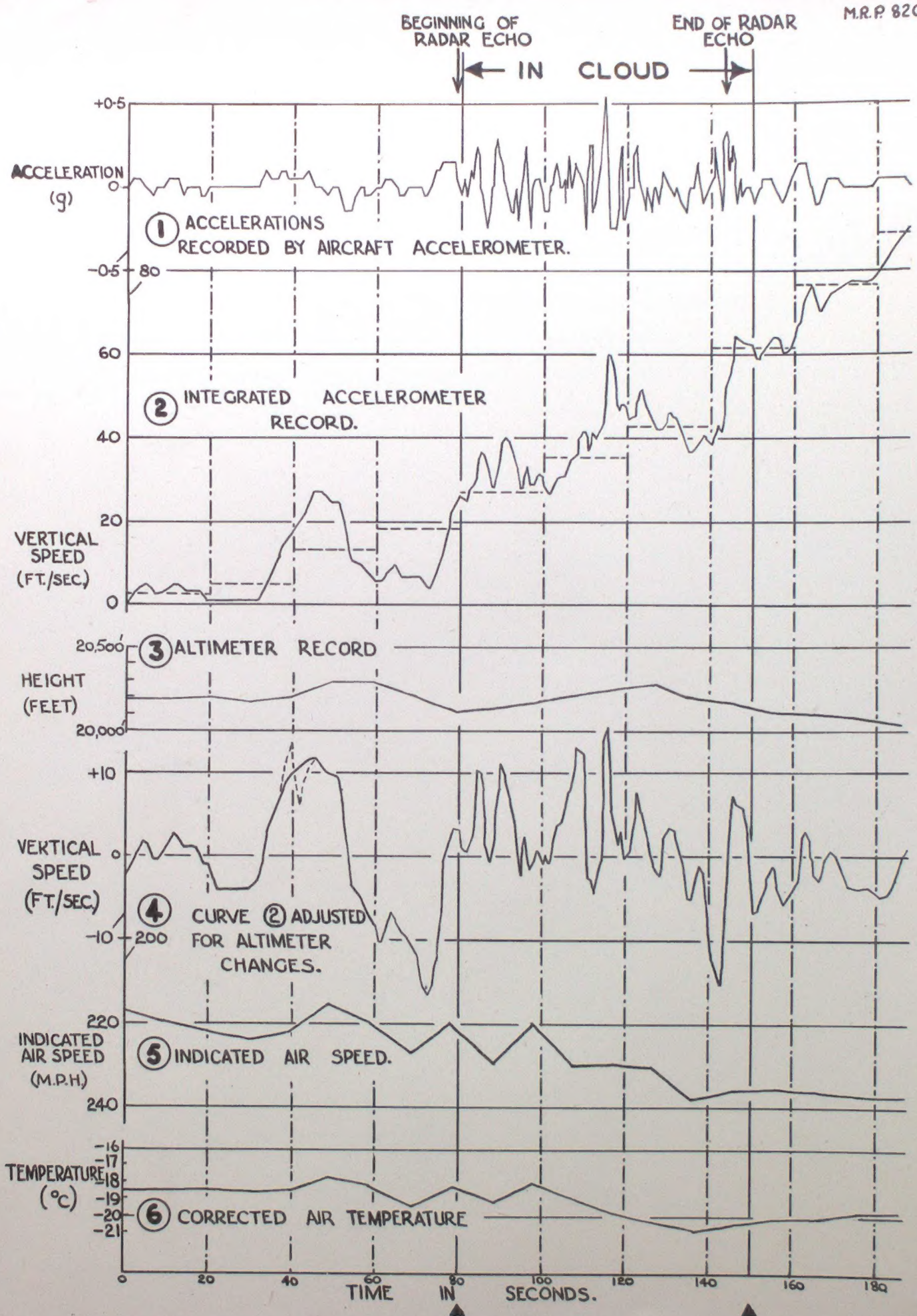


FIG. IV. CUMULONIMBUS INVESTIGATION-13TH JUNE 1952-RUN 4- 20,200'

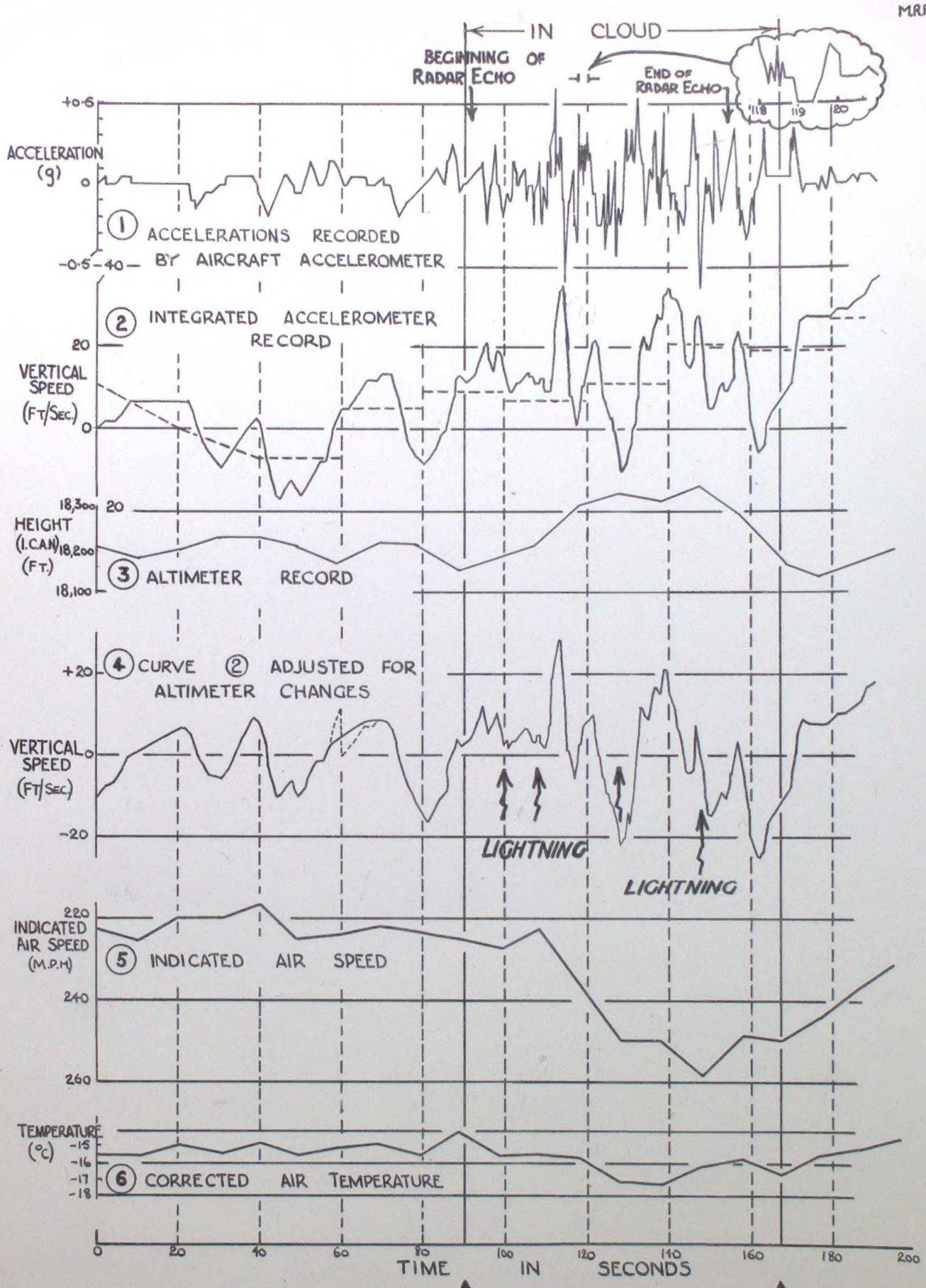
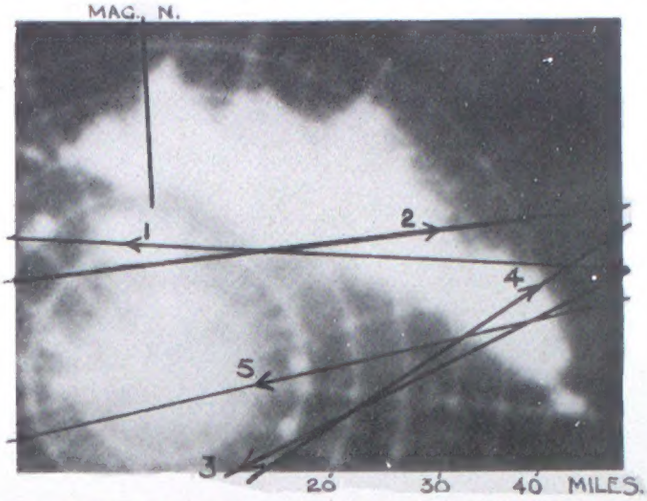


FIG. V. CUMULONIMBUS INVESTIGATION - 13TH JUNE 1952 - RUN 5 - 18,200'

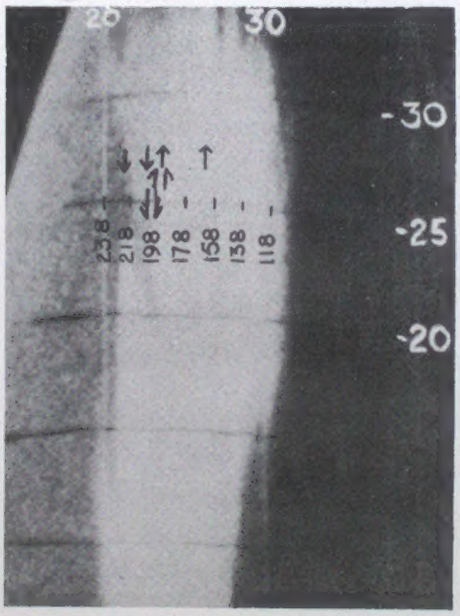
RADAR ECHO PHOTOGRAPHS FOR THUNDERSTORMS OF 13TH JUNE 1952

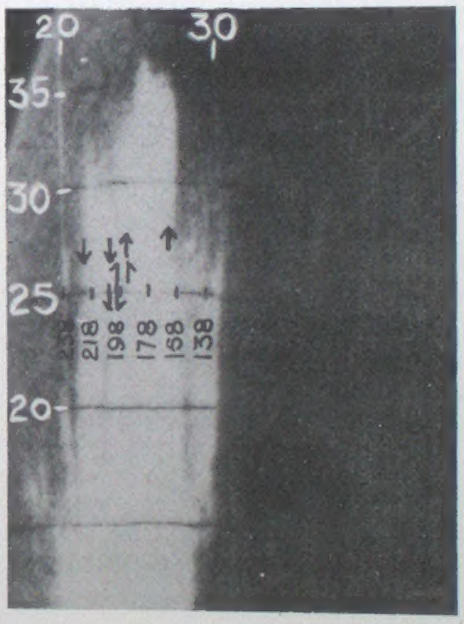
IN HEIGHT/RANGE PHOTOGRAPHS ↑,↓ INDICATE UP AND DOWN GUSTS & 1↑, J↓ UP AND DOWN CURRENTS.



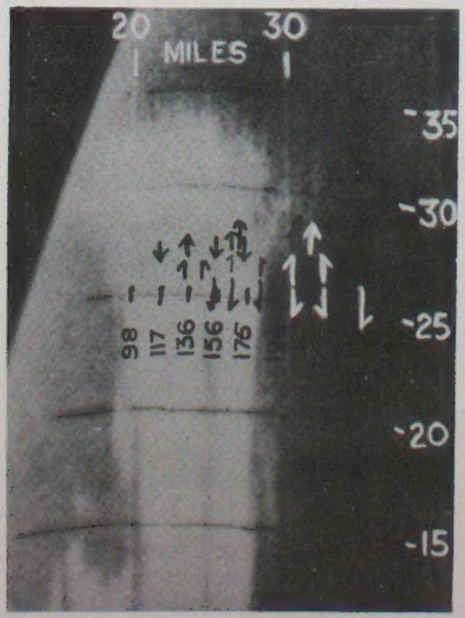
ON PHOTOGRAPHS RANGES ARE GIVEN IN STATUTE MILES AND HEIGHTS IN THOUSANDS OF FEET.

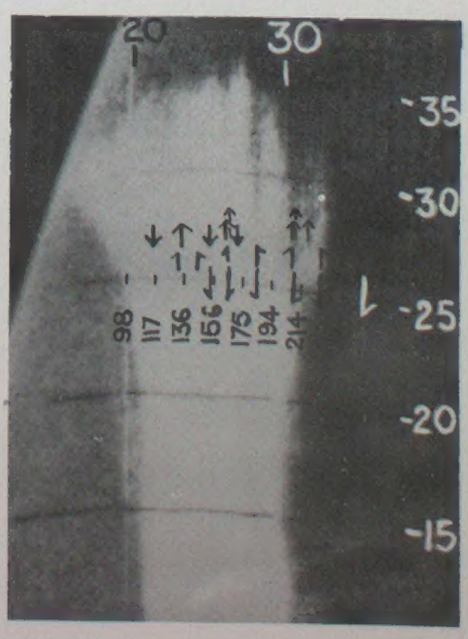
P.P.I. PHOTOGRAPH TAKEN 3 MINUTES AFTER RUN 5. THE TRACKS OF THE AIRCRAFT ARE SHOWN.



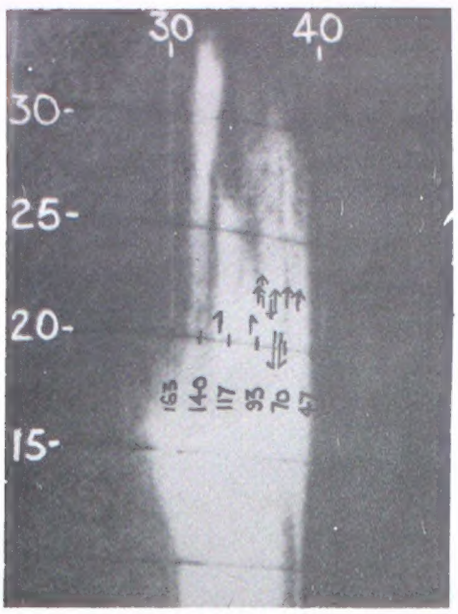


081°M. 112 SECS. ← RUN I . → 070°M. 237 SECS.

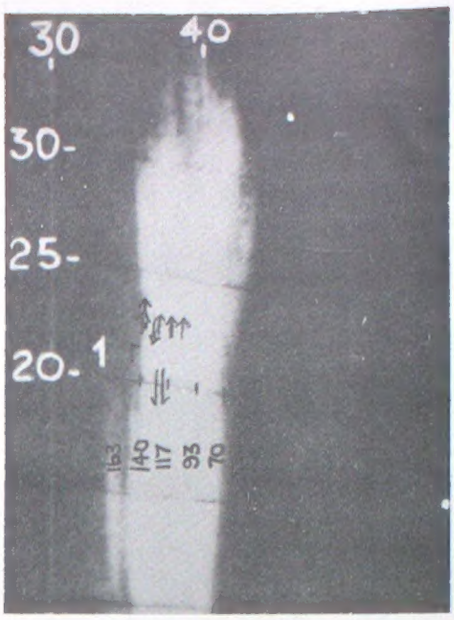




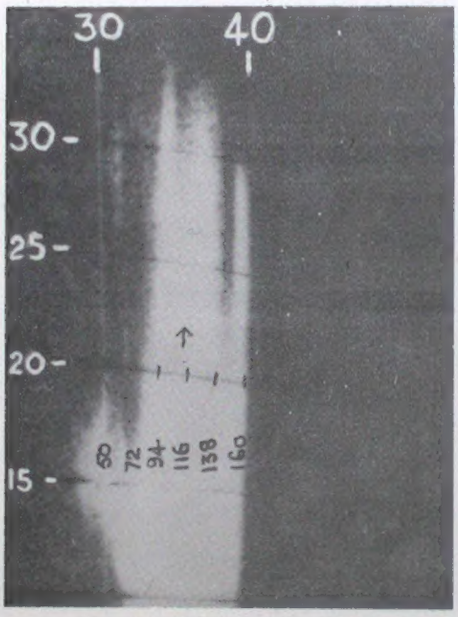
060°M. 129 SECS. ← RUN II → 070°M. 185 SECS.



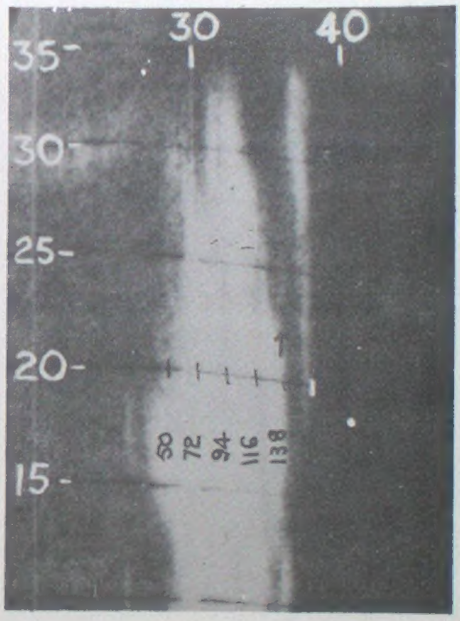
087°M. 50 SECS. — RUN III —



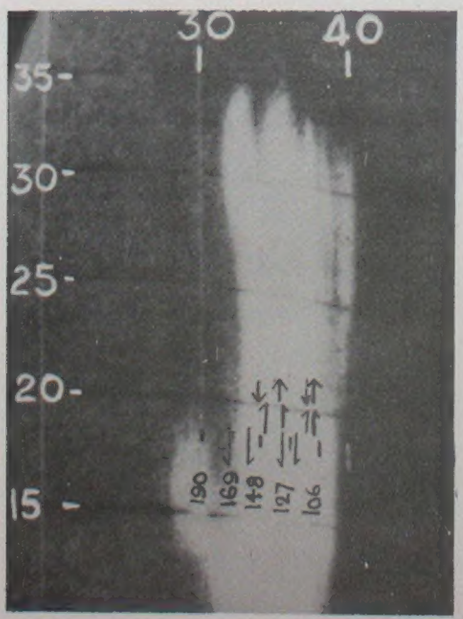
093°M. 163 SECS.



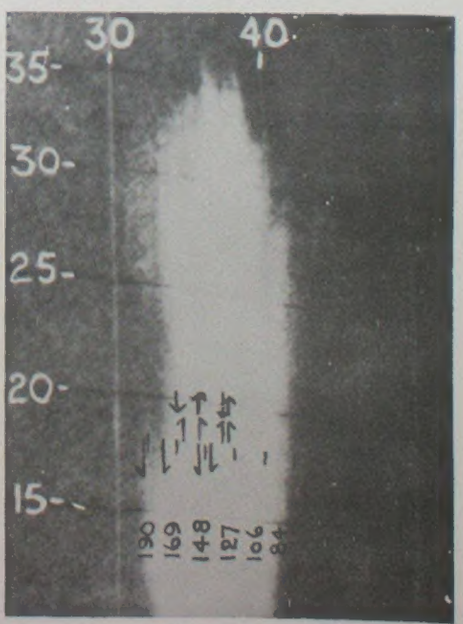
085°M. 69 SECS. — RUN IV —



081° 185 SECS.



083°M. 25 SECS. — RUN V —



087°M. 194 SECS.